Int J Adv Manuf Technol (2014) 75:1723–1733
DOI 10.1007/s00170-014-6269-6

ORIGINAL ARTICLE

Effect of projection on joint properties of friction welding of tube-to-tube plate using an external tool

S. Senthil Kumaran · S. Muthukumaran

Received: 25 March 2011 / Accepted: 10 August 2014 / Published online: 28 August 2014

Abstract Friction welding is widely used as a mass-production method in various industries. Friction welding of tube-to-tube plate using an external tool (FWTPET) is an innovative friction welding process and has potential applications in aerospace, railways, automotive, and marine industries. FWTPET is capable of welding tube-to-tube plate of similar and dissimilar metals and is capable of producing good-quality leak-proof weld joints. In this work, FWTPET welds have been produced with six different tube projections. Tool steel has been used to join the FWTPET process. After the completion of welding, macrostructural and microstructural studies have been conducted and it reveals the weld configuration that is capable of generating defect-free welds. Further, hardness and pull strength of welds obtained with six different tube projections have been studied. When compared to other weld conditions, 1 mm projection has resulted in better strength. The weld strength and average weld interface hardness with 1 mm projection are 84.72 MPa and 70.58 Hv respectively. The sufficient heat generation has been occurred at optimum projection in FWTPET process.

Keywords Welding · Friction welding · Tube-to-tube plate welding · Microstructural study · Hardness · Pull strength

S. S. Kumaran
Department of Mechanical Engineering, RVS Educational Trust's Group of Institutions, RVS School of Engineering and Technology, Dindigul 624005, Tamil Nadu, India
e-mail: sskumaran@ymail.com

S. Muthukumaran (✉)
Department of Metallurgical and Materials Engineering, National Institute of Technology, Tiruchirappalli 620015, Tamil Nadu, India
e-mail: pondymuthu@gmail.com

1 Introduction

Friction welding is used in many fields and has widespread industrial applications as a mass-production process for joining similar as well as dissimilar materials, and the procedure is relatively simple [1]. However, there are still unresolved issues in this method such as the difficulty in setting the appropriate welding conditions for some materials and variance of optimum welding conditions between friction welding machines. Friction welding is a solid-state bonding process, and friction welding technologies convert the mechanical energy into material deformation and heat energy to create a weld. Friction welding is a method for making welds in which one component is rotated relative to, and in pressure contact, with the mating component to produce heat at the faying surfaces. The weld is completed by the application of a forge force after the cessation of relative motion. The weld is characterized by a narrow heat-affected zone, flash surrounding the joint, and the absence of a fusion zone. Compared with other welding processes, this process has several advantages. Friction welding is a method of manufacturing which is being used extensively in recent times due to its advantages such as low heat input, production time, ease of manufacture, and environment friendliness. Friction welding can be used to join different types of ferrous metals and nonferrous metals that cannot be welded using existing fusion welding methods. It is a solid-phase welding process that joins two materials by the friction heat generated by the relative motion of the contact surfaces under the action of an upset pressure. Some of the disadvantages of liquid-phase manufacturing methods like high heat input and usage of nonmatching filler wire can be avoided using friction welding. In order to produce good-quality weld joints, it is vital to set proper welding process parameters. Generally, the welding process is a multi-input and multi-output process in which there exists a close relationship between the quality of joints and the welding parameters. This process of identification of suitable combination of input process parameters so as to produce the desired output parameters necessitates the conduct of several experiments which consumes significantly cost and time. Several efforts have been taken to understand the effect of process parameters on material flow behavior, microstructural formation, and mechanical properties of friction-welded joints [2, 3]. As a milestone in the field of friction welding, the process of friction welding of tube-to-tube plate using an external tool (FWTPET) was invented in the year 2006 and a patent was granted in the year 2008 (by one of the present authors [4]). FWTPET is an innovative solid-state joining process in which the material that is being welded does not melt and recast [1]. Due to the absence of parent metal melting, the FWTPET process is observed to offer several advantages over fusion welding such as the absence of solidification cracks and porosity. In this research study, FWTPET process has been carried to achieve high-quality leak-proof joints. Major advantages of this process include capability to join dissimilar metals that may not be possible using fusion welding techniques [5]. Joints made by FWTPET process exhibit enhanced mechanical, metallurgical properties with lesser energy consumption. Important process parameters of FWTPET include tool rotational speed, shoulder diameter, and clearance between pin and tube. The potential application of FWTPET joints includes catch cans in automobile engines, box type heat exchangers, collector with aluminum absorber, aluminum evaporator used in household air conditioners, and solar panel backing. In this research work, the tube is prepared with different projection, and FWTPET welding process has been carried out. The macrostructural and microstructural studies have been conducted for different tube projections in weld joints, followed by the measurement of hardness and pull strength. The metal flow phenomenon during FWTPET is discussed based on the obtained results. The results of this study would also indicate the best weld joint as well as the best weld condition that leads to the production of high-quality leak-proof weld joints, which finds applications in different fields.

2 Experimental procedure

2.1 FWTPET process

The FWTPET machine developed in-house is shown in Fig. 1. The external tool consists of a shoulder and pin which is shown in Fig. 2. The tube to be welded is cleaned, and holes or slots are prepared along the faying surface of the tube. A suitable hole is drilled in a plate, and the tube is fitted and assembled in FWTPET machine table. The FWTPET machine consists of tool holder, spindle, table, and supporting structure. The tool is lowered while in rotation, and heat is generated due to friction when the shoulder touches the plate. The plastic flow of metal takes place toward the center of the tool axis [6–8]. The metal flows through the holes in the tube and occupies the gap between the pin and inner diameter of the tube. The tool is withdrawn after predetermined time. The material movement is restricted by the cylindrical pin, and forging of metal takes place between the tube and the plate [8–10]. Due to the combined effects of high pressure and temperature between the faying surfaces, good metallurgical bonding occurs [10–13]. Both the tube and plate used in the present study are made of commercial pure aluminum, and their chemical composition is shown in Table 1. Tools made of

Fig. 1 FWTPET machine (developed in-house)

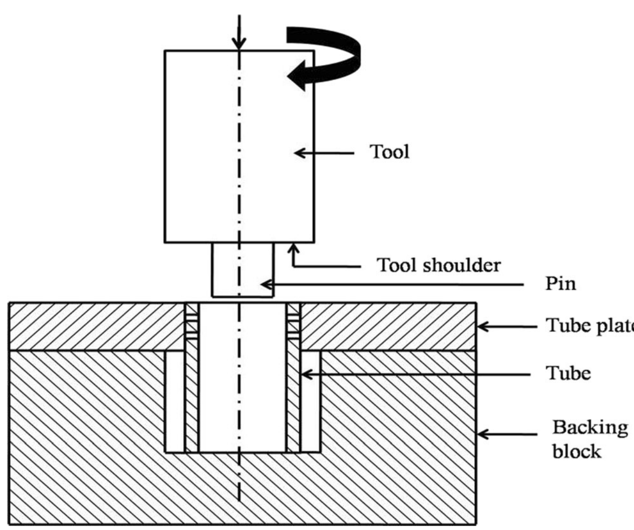


Fig. 2 Schematic diagram for FWTPET setup (clearance method)

Table 1 Chemical composition of parent metal

	Element									
	Al	Si	Fe	Cu	Mg	Mn	Ti	Zn	Cr	V
wt%	Bal	0.0006	0.0007	0.0013	0.0021	0.0001	0.0001	0.0002	0.0001	0.0001

Table 2 Tool steel chemical composition

	Element								
	Fe	C	Mn	Si	Cr	Ni	Mo	W	V
wt%	Bal	0.87	0.36	0.30	3.71	0.31	4.31	0.95	2.05

tool steel have been used to fabricate FWTPET joints in the present study, and the chemical composition of tool material is shown in Table 2. Commercial pure rolled aluminum plates of 6 mm thick are cut into the required size (50 mm×70 mm) using a power hacksaw, and suitable external diameter tubes have been cut into required sizes. Then, the diameter holes are created according to the tube diameter and drilled in the center of the plates. Tool used in the present study is made of tool steel for fabricating FWTPET joints. The backing block employed in FWTPET process is shown in Fig. 3. The assembled workpiece is fixed on the machine table with the fixtures, and the tool has been fixed to the spindle.

2.2 Experimental investigation of six different tube projection conditions

Six different tube conditions used in the present investigation are shown in Table 3. Six tubes with different tube projections for FWTPET process are shown in Fig. 4a. The assembly of six tubes with different projections inserted in the plates before welding is shown in Fig. 4b. The above six types of different tube projection preparations are shown in Fig. 5a–f. In order to remove oxide film on the faying surfaces, both the tubes and tube plates are cleaned with a wire brush and washed in the acetone solution before welding. The tubes are assembled into the tube plate, and the process parameters used in the present investigation are tool rotational speed, shoulder diameter, feed rate, and pin clearance whose values are 1,030 rpm, 30 mm, 0.2 mm/min, and 1 mm, respectively. For all six different types of tube projection preparations, the welding has been carried out using the above process parameters. The assembly of six tubes with different projections after welding in the bottom and top sides is shown in Fig. 6a, b, respectively. Joints are prepared for pull test, and the tests have been conducted using a tensometer. A pull test specimen fixed in the tensometer is shown in Fig. 7.

2.3 Macrostructure studies

After the completion of welding, the tube-to-tube plate joints are sliced for macrostructural studies. The rough scratches on the surfaces have been removed using a belt grinder. The fine scratches have been removed using emery sheet of different grades, and further polishing is done using alumina and diamond paste using a disk-polishing machine. This is followed by etching the macrostructures using Tucker's reagent (composition—4.5 ml HNO_3, 2.5 ml H_2O, 1.5 ml HCl, 1.5 ml HF). Then, the samples have been washed, dried, and observed in a macroscope.

Fig. 3 Backing block used in FWTPET process

Table 3 Tube projection values

S. No	Tube conditions	Tube projection values
1	Condition 1	Tube with "−1-mm" projection
2	Condition 2	Tube with "0-mm" projection
3	Condition 3	Tube with "1-mm" projection
4	Condition 4	Tube with "2-mm" projection
5	Condition 5	Tube with "3-mm" projection
6	Condition 6	Tube with "4-mm" projection

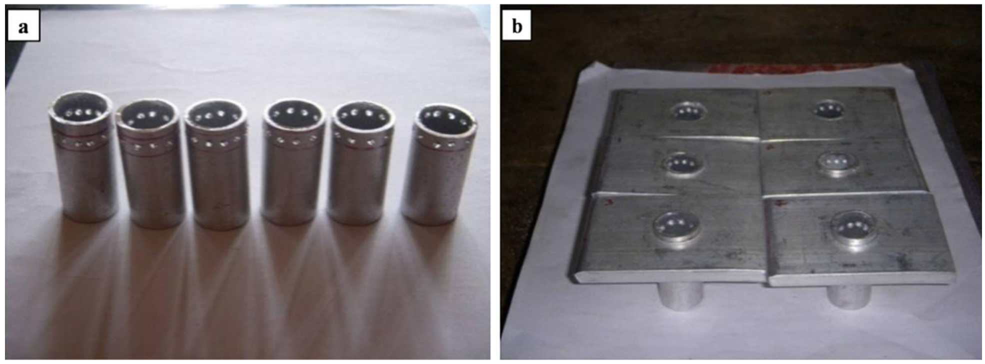
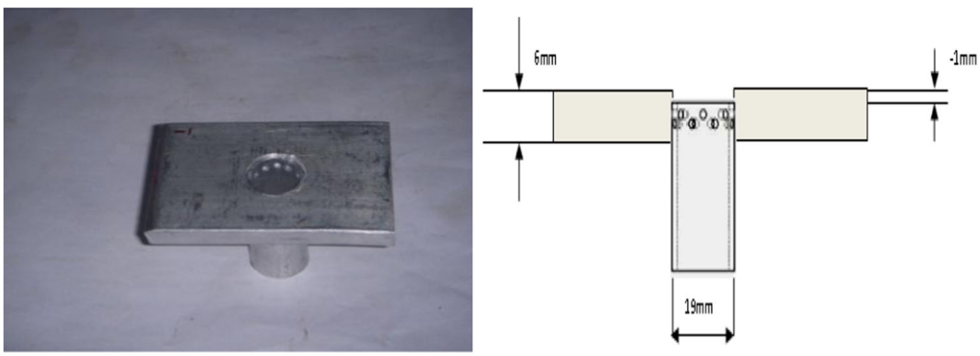
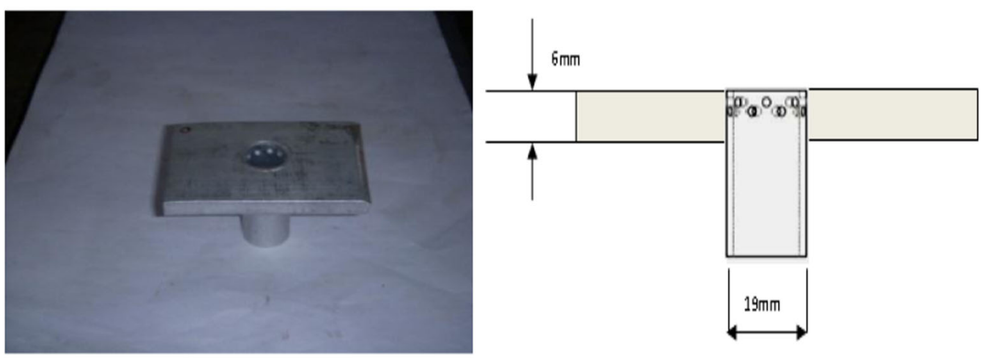


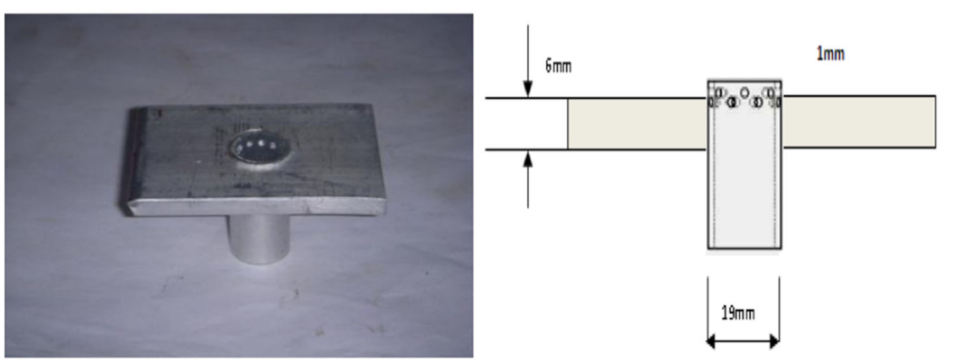
Fig. 4 **a** Tubes for FWTPET process. **b** Assembly of tubes with different projection in the plates



(a) Condition-1

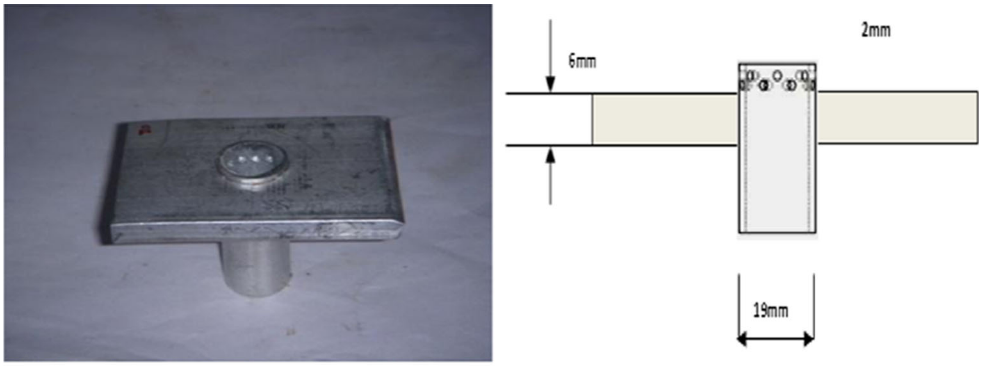


(b) Condition-2

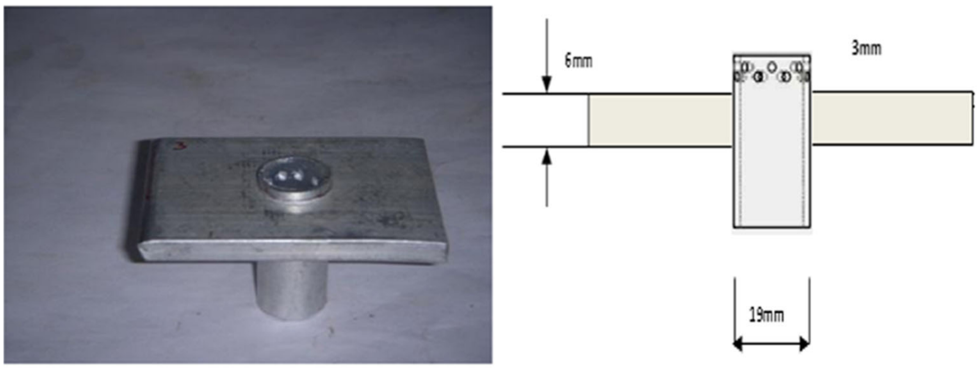


(c) Condition-3

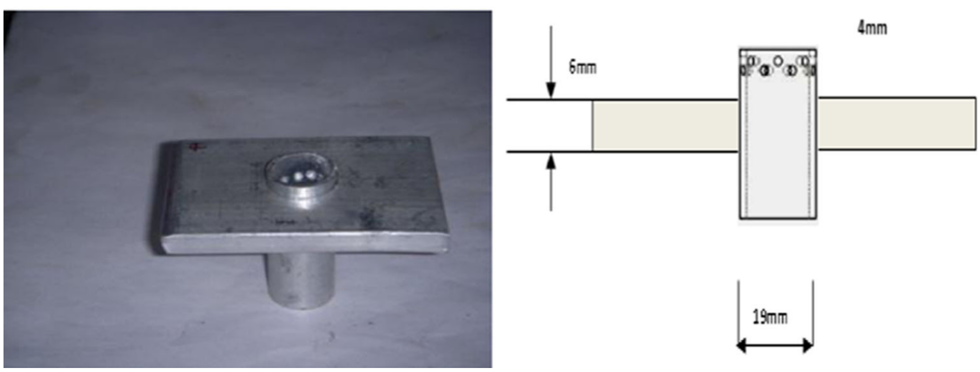
Fig. 5 Photographs and sketch of tube and tube plate assemblies. **a** Condition 1. **b** Condition 2. **c** Condition 3. **d** Condition 4. **e** Condition 5. **f** Condition 6



(d) Condition-4



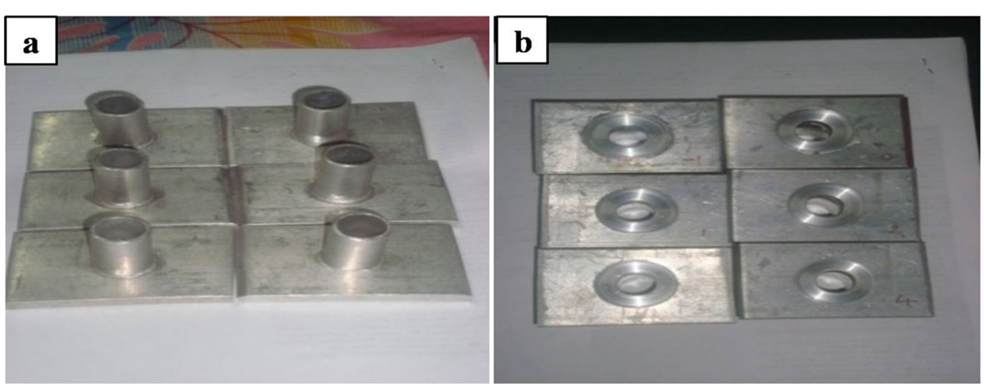
(e) Condition-5



(f) Condition-6

Fig. 5 (continued)

Fig. 6 Tube-to-tube plate welds (**a** bottom view, **b** top view)



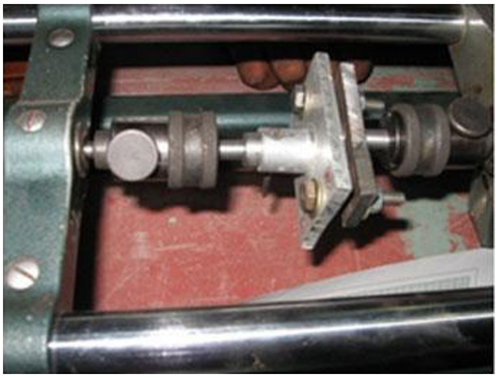


Fig. 7 Tube-to-tube plate joint loaded in a tensometer

2.4 Microstructure studies

The microstructure aspects of the friction-welded joints are studied through optical microscopy. The integrity of joints has been analyzed through the micrographs at the weld zone. The Keller's etchant has been used for microstructure studies (composition—2 ml HF, 3 ml HCl, 5 ml HNO_3, 190 ml distilled water).

3 Results and discussions

The hardness has been measured for the welds obtained with six different tube projection conditions using Vickers's hardness tester. The Vickers's hardness (Hv) has been measured at the interface area, and the results are shown in Fig. 8. The pull test sample (prepared from condition 1) before and after testing is shown in Fig. 9a, b, respectively. Some of the specimens have fractured away from the joint, and maximum pull strength has been achieved using the FWTPET process. The macrostructural observation pertaining to six different tube projections is shown in Fig. 10a–f, respectively. Based on the macrostructural observation, it is found that the weld conditions 3 and 4 can produce defect-free welds, whereas weld conditions 1, 2, 5, and 6 are susceptible to defects as shown in Fig. 10a–f, respectively. Weld conditions 1, 2, 5, and 6 are more prone to defect when compared to other weld conditions due to insufficient bonding between the tube and tube plate. The variation of hardness and pull strength for six different weld conditions are shown in Fig. 11. Based on the inferences from Fig. 11, it has been found that weld conditions

Fig. 8 Graph drawn between hardness and distance from centerline of the weld

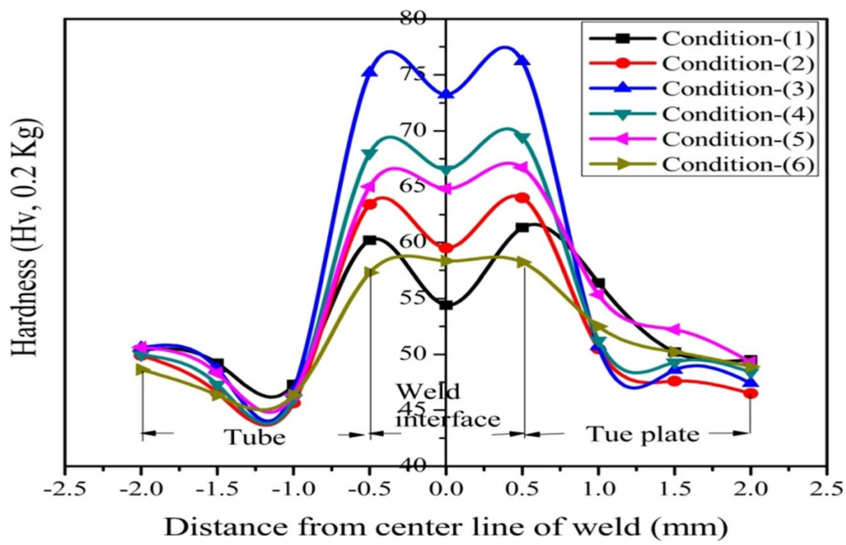
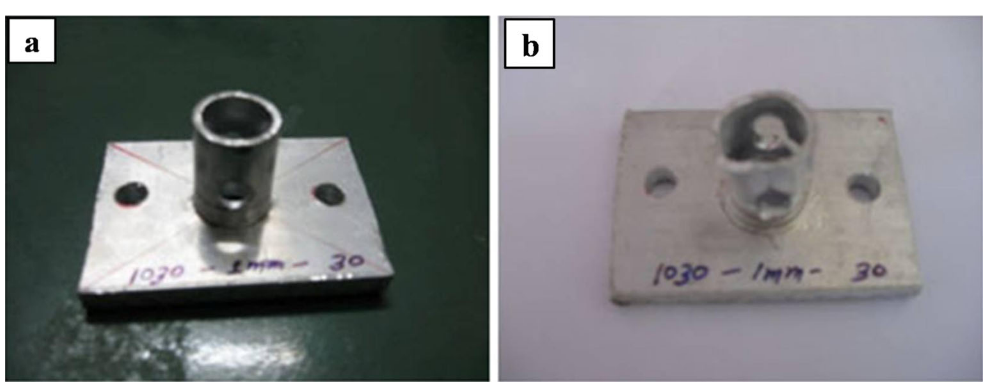


Fig. 9 **a** Pull test sample. **b** Fractured pull test sample



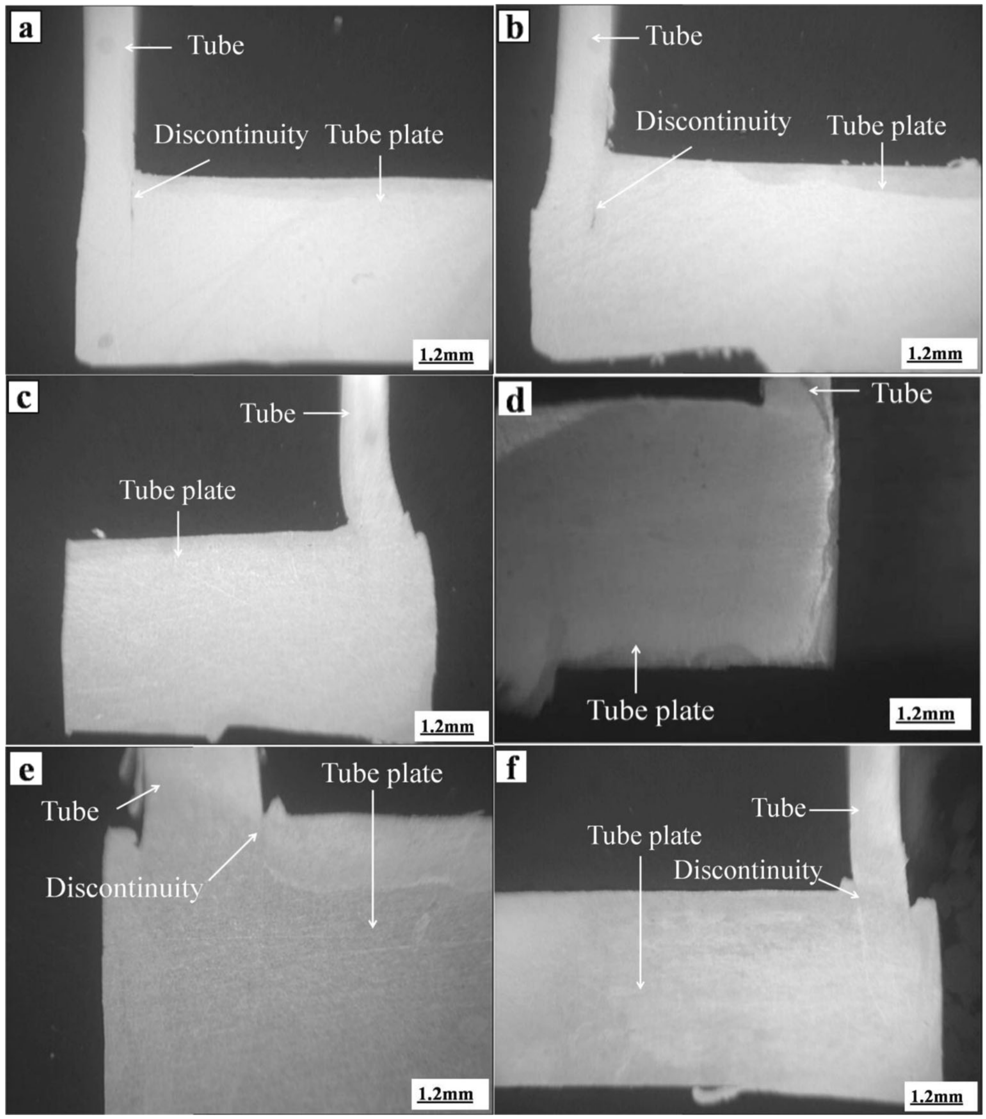


Fig. 10 Macrostructures of FWTPET weld joint. **a** Condition 1 (−1-mm projection). **b** Condition 2 (0-mm projection). **c** Condition 3 (1-mm projection). **d** Condition 4 (2-mm projection). **e** Condition 5 (3-mm projection). **f** Condition 6 (4-mm projection)

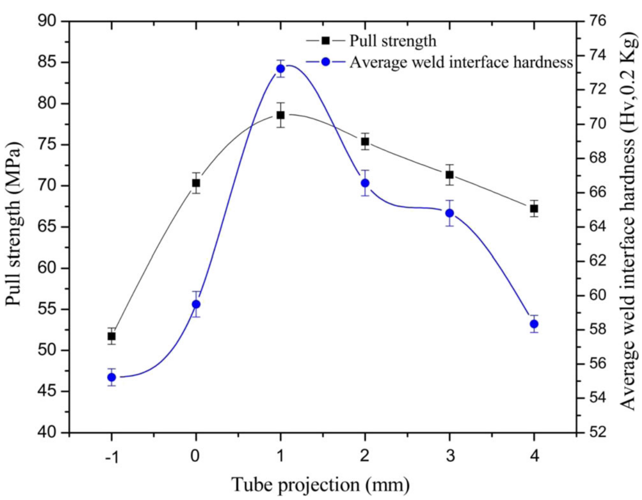


Fig. 11 Pull strength and hardness for six different tube conditions

3 and 4 possess both maximum hardness at the interface and maximum pull strength. The weld conditions 3 and 4 reveal high weld strength and hardness due to better metallurgical bonding between the tube and tube plate. The reason for good strength in weld conditions 3 and 4 introduces sufficient heat between tube and tube plate. The tool is lowered during rotation, and heat has been created by the tool shoulder due to friction, when it touches both the tube and the tube plate. During the same time, the projection of the tube is also optimum so that better bonding between tube and tube plate has been achieved due to sufficient heat generated. In this case, the metal flow has been introduced in two directions: first direction toward center of the tool axis while touches the tube surface and second direction toward outward of the tube center when the shoulder touches the tube plate using the tool shoulder (shown in Fig. 12) so that required amount of heat is

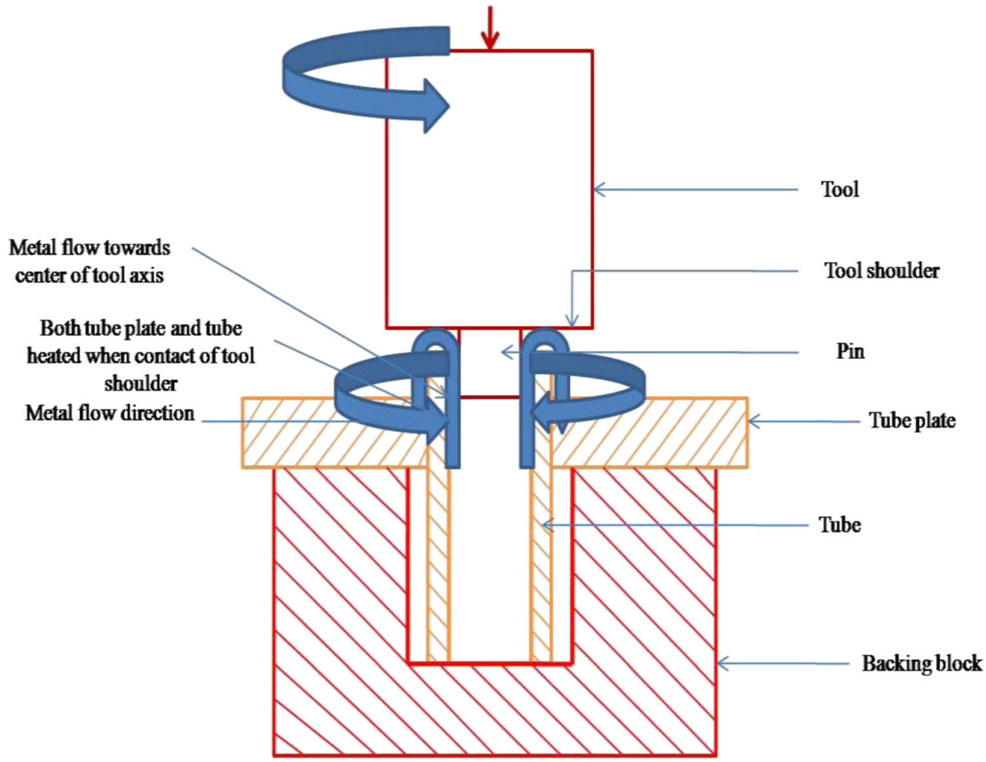


Fig. 12 Metal flow direction (weld conditions 3 and 4)

created between the tube and tube plate. However, the strength and hardness decrease at the weld conditions 1, 2, 5, and 6 due to insufficient bond between the tube and tube plate. The projection in the weld conditions 1 and 2 is −1 and 0 mm. For both the weld conditions 1 and 2, there is no projection of the tube when compared with other weld condition, and also

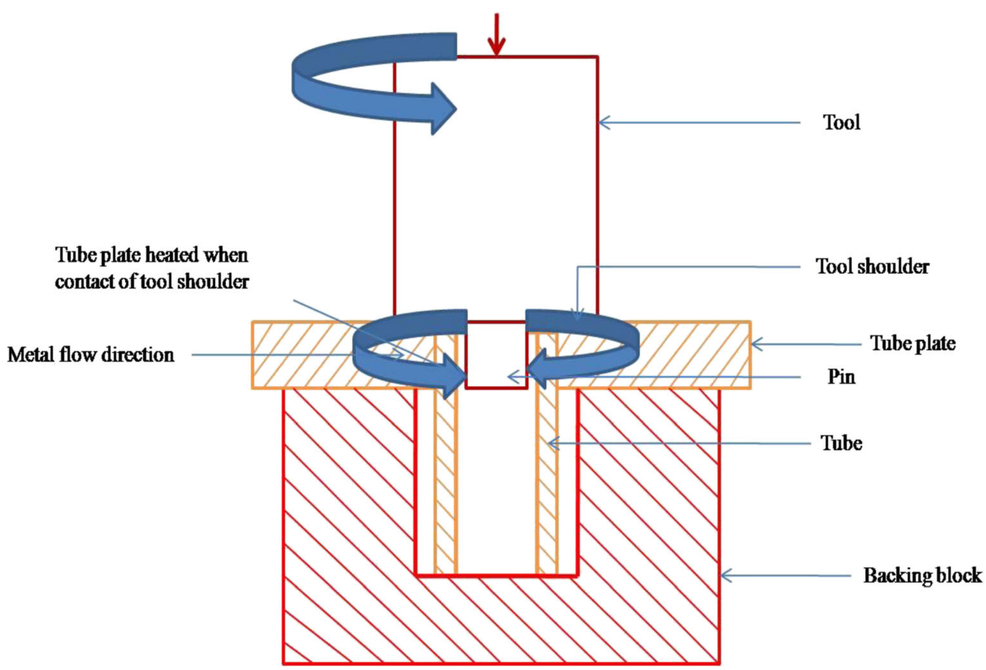


Fig. 13 Metal flow direction (weld conditions 1 and 2)

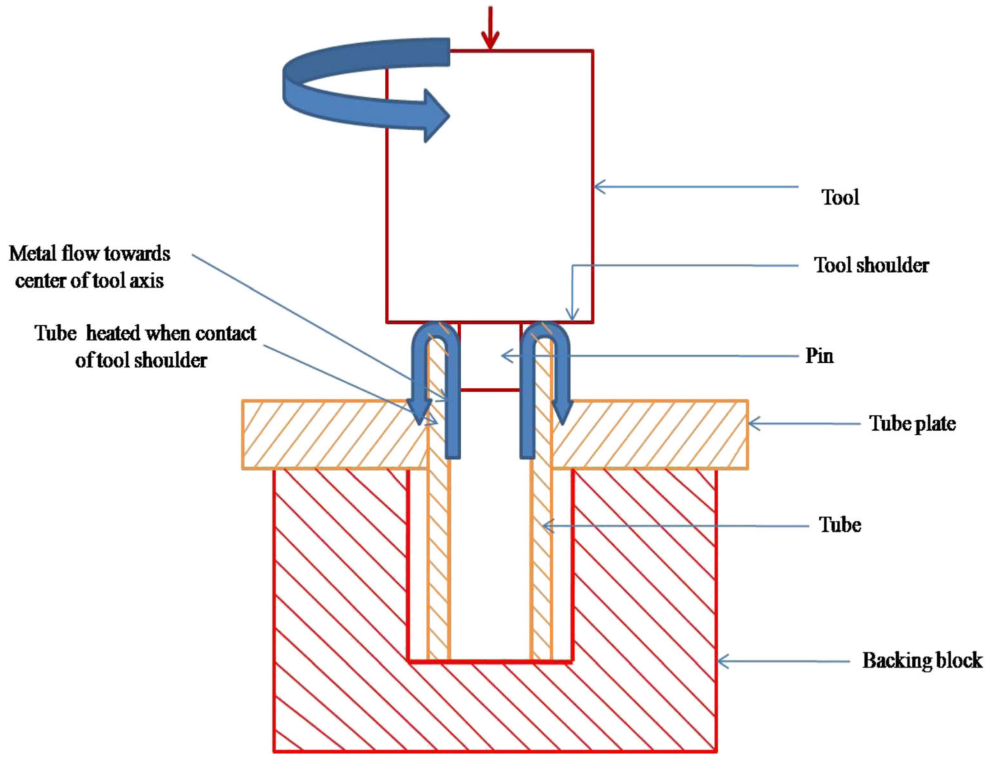


Fig. 14 Metal flow direction (weld conditions 5 and 6)

heat is created due to friction, only at the plate surface so that there is no sufficient heat created in the tube portion during tool rotation. The main reason is that there is no projection of the tube, and also, the tool shoulder touches only the tube plate while lowering the tool as shown in Fig. 13. Hence, the small penetrations have been created at the top of the plate during welding and occupy the metal flow at the center of the tool axis from the plate surface. For this reason, extra amount of force and time has been required to achieve the metal flow between the tube and tube plate. Weld conditions 5 and 6 are achieved with projections from the plate surface. Hence, the tool shoulder touches the outer surface of the tube at the first stage, and the projection of the tube is slightly higher than the other weld conditions 3 and 4 so that the metal flow got initiated only from the tube surface and continuously takes place at the center of the tool axis up to the end of the weld as is shown in Fig. 14. The projection of the tube is compensated for occupying the metal flow between the tube and tube plate, and also, less force is sufficient during welding. When compared with other weld conditions 1 and 2, high amount of force is necessary for occupying the metal flow from the plate surface, even though the weld conditions 5 and 6 have introduced more projection when compared with weld conditions 3 and 4. But, the weld conditions 5 and 6 possess less strength and hardness when compared with weld conditions 3 and 4. The main reason for decrease in strength and hardness with higher projection is due to insufficient heat generation between the tube and tube plate. As the tool shoulder touches more tube area, large quantity of heat is generated only along the tube side. During the same time, the tool contact has been more focused on tube surface, and also tube bending occurs slightly during welding. The friction-welded joints have been sectioned perpendicular to the bond line and observed using optical microscope. Typical micrographs showing different morphology of microstructures at different zones of the friction-welded joints have been presented and analyzed. Compared to base metal, the changes in microstructures are observed obviously at weld zone interface. The grains at base metal (plate and tube) are relatively coarser. Fine grain structure has been observed in the weld zone interface. In solid-state welding, especially in friction welding, due to severe deformation, the refined grain structure is observed at the weld zone which resulted in improved properties [12, 13]. An investigation on different tube projections with different microstructure conditions is depicted in Fig. 15a–f, respectively. From the above microstructures, it is clearly observed that the interface size varied according to the tube projection. The grain size is also affected at the interface with respective tube projection. This mainly happened when contact of the tool shoulder between tube and tube plate depends on the

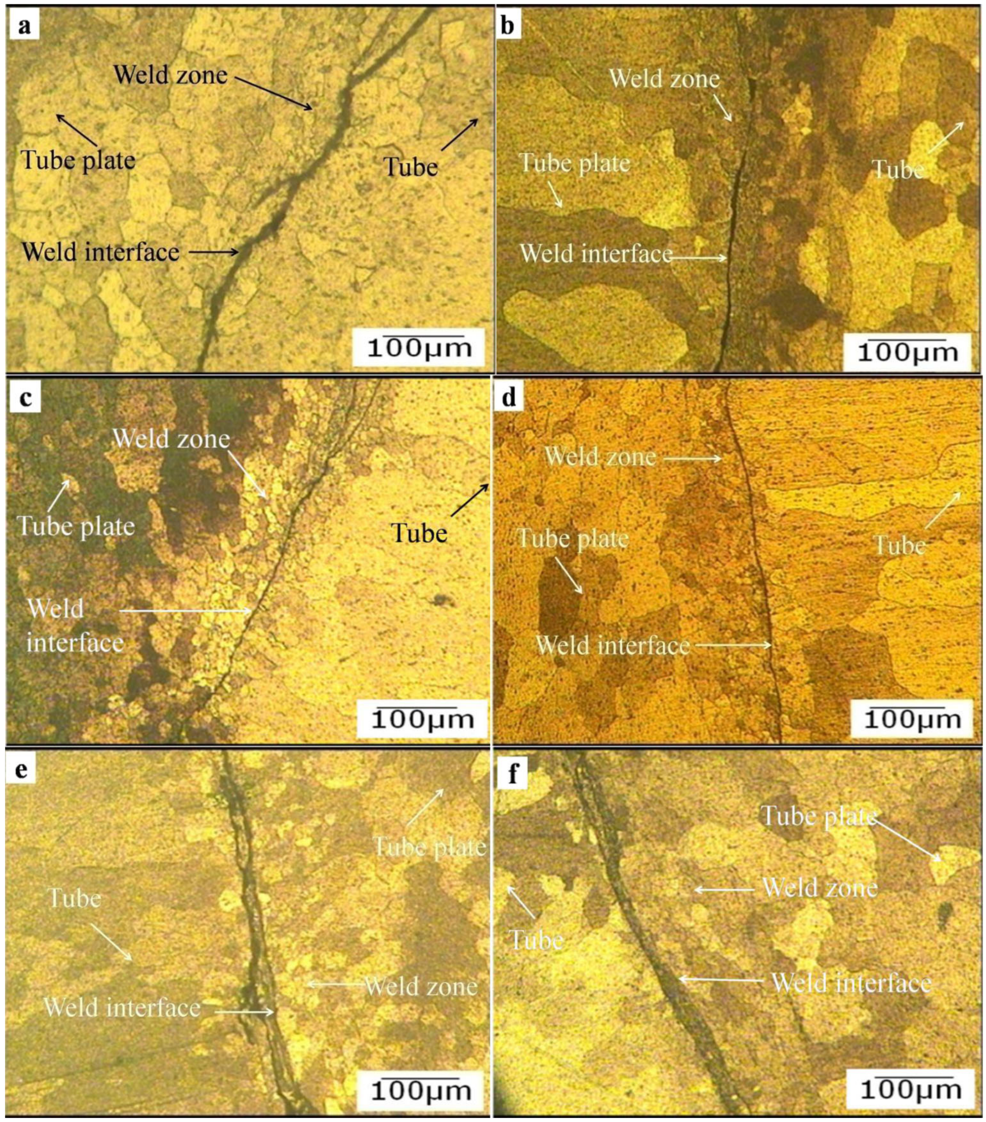


Fig. 15 FWTPET weld microstructures at different conditions. **a** Condition 1 (−1-mm projection). **b** Condition 2 (0-mm projection). **c** Condition 3 (1-mm projection). **d** Condition 4 (2-mm projection). **e** Condition 5 (3-mm projection). **f** Condition 6 (4-mm projection)

projection of the tube and also changes in metal flow pattern and heat generation during welding.

4 Conclusions

Solid-state welding process possesses several advantages and is widely used in industries. Friction welding is a solid-state joining process which is capable of joining similar or dissimilar metals. In order to reduce fabrication cost, researches have been exploring the newer welding process to improve joint properties. FWTPET is a novel invention in this direction and has numerous industrial applications. This process is capable of producing high-quality tube-to-tube plate weld joints with enhanced mechanical and metallurgical properties. In this study, six different tube projection conditions have been subjected to FWTPET welding. The macrostructural study indicates that weld performed with “1-mm” projection and weld performed with “2-mm” projection are defect-free, whereas weld performed with “−1-mm” projection, “0-mm” projection, “3-mm” projection, and “4-mm” projection are prone to defects. Further, the present study indicates that weld conditions 3 and 4 possess higher hardness along the interface and higher pull strength when compared to other weld conditions. The present study may help the engineers to predict the kind of weld condition that is capable of producing high-quality weld joints in industries.

Acknowledgments The authors wish to express their sincere thanks to the Ministry of Human Resource Development (MHRD), Government of India, for the financial support to carry out this investigation.

References

1. Brien RLO (1991) Welding handbook, vol 2, 8th edn. American Welding Society, Miami
2. Muthukumaran S (2010) Friction welding of tube to tube plate using an external tool—a study. Int Weld Symp 2010:241–245
3. Senthil Kumaran S, Muthukumaran S, Vinodh S (2010) Optimization of friction welding of tube to tube plate using an external tool. Struct Multidiscip Optim 42:449–457
4. Muthukumaran S (2006) A process for friction welding tube to a tube sheet or plate by adopting an external tool. Indian patent application no. 189/KOL/06, 7 Mar 2006. Patent no. 217446, 26 Mar 2008
5. Muthukumaran S, Senthil Kumaran S, Kumar S (2011) Friction welding of Cu-tube to Al-tube plate using an external tool. Trans Indian Inst Met 64:255–260
6. Muthukumaran S, Pradeep C, Vijaya Kumar C, Senthil Kumaran S (2010) Mechanical and metallurgical properties of aluminium 6061 alloy tube to tube plate welded joints welded by friction welding using an external tool process. Int Weld Symp 2010:235–239
7. Senthil Kumaran S, Muthukumaran S, Vinodh S (2010) Taguchi method and genetic algorithm based optimization of FWTPET process parameters. In: International Conference on Frontiers in Mechanical Engineering (FIME 2010), p 60
8. Senthil Kumaran S, Muthukumaran S, Vinodh S (2010) Experimental and numerical investigation of weld joints produced by friction welding of tube to tube plate using an external tool. Int J Eng Sci Technol 2:109–117
9. Senthil Kumaran S, Muthukumaran S, Vinodh S (2011) Optimization of friction welding of tube to tube plate using an external tool by hybrid approach. J Alloys Compd 509:2758–2769
10. Senthil Kumaran S, Muthukumaran S, Chandrasekhar Reddy C (2011) Effect of tube preparations on joint strength in friction welding of tube-to-tube plate using an external tool process. Exp Tech. doi:10.1111/j.1747-1567.2010.00700.x
11. Senthil Kumaran S, Muthukumaran S, Vinodh S (2011) Optimization of friction welding of tube-to-tube plate using an external tool by Taquchi method and genetic algorithm. Int J Adv Manuf Technol. doi:10.1007/s00170-011-3286-6
12. Senthil Kumaran S, Muthukumaran S, Venkateswarlu D, Balaji G.K, Vinodh S (2011) Eco-friendly aspects associated with friction welding of tube-to-tube plate using an external tool process. Int J Sustainable Eng. doi: 10.1080/19397038.2011.570877
13. Senthil Kumaran S, Muthukumaran S, Chandrasekhar Reddy C (2011) Suitability of friction welding of tube to tube plate using an external tool process for different tube diameters—a study. Exp Tech. doi:10.1111/j.1747-1567.2011.00765.x